

The Citizen Explorer Design and Operations Planning System

Jason Willis¹
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-0765
willisj@jpl.nasa.gov

Gregg Rabideau
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-5364
Gregg.R.Rabideau@jpl.nasa.gov

Colette Wilklow
Colorado Space Grant College
Campus Box 520
Boulder, CO 80309
303-492-4383
wilklow@colorado.edu

Abstract—The Citizen Explorer Design and Operations Planning System (CXDOPS) was developed by the Colorado Space Grant College as a comprehensive mission design, systems modeling and mission operations tool. This system provides visibility into how changes in mission architecture affect system performance throughout all phases of the project. Additionally it will provide manual and automated scheduling capabilities for satellite commanding over the course of mission operations.

TABLE OF CONTENTS

1. INTRODUCTION
2. THE CITIZEN EXPLORER MISSION
3. SYSTEM HISTORY
4. CXDOPS IMPLEMENTATION
5. DESIGN VISUALIZATION
6. MISSION OPERATIONS
7. SUMMARY

1. INTRODUCTION

This paper will describe the design and mission operations planning system that will be used in support of the Citizen Explorer satellite when it is launched in October of 1999. Citizen Explorer - I (CX - I) is the first in a series of satellites being designed and built by students at the Colorado Space Grant College. CX-I is designed as a Delta II secondary payload and is currently manifested with the Earth Orbiter-1 (EO-1) and SAC-C missions. The mission concept is that the satellite will take data relating to ozone and downlink that data directly to amateur users (primarily schools) on the ground where they will be able to analyze the data themselves and compare the results with measurements from other regions of the world.

An additional objective is to demonstrate advanced mission operations technologies for use by future spacecraft. Specifically CX-I will be exploring autonomous command and control software running on the satellite and the ground systems and automated planning and scheduling running on the ground system.

The CXDOPS was conceived as a way to merge system design analysis with the analysis and planning needs of the mission operations subsystem. During the mission and system design it was used to visualize power profiles as well as to determine the optimal solar array configuration for CX-I's planned orbit and how this was affected by changes in the orbit. During mission operations it will be integrated into the End-to-End Mission Operations System (EEMOS) and will generate the schedule for the spacecraft autonomously. Once verified by the user, the schedule will be sent to the ground command and control system for uplink to the spacecraft.

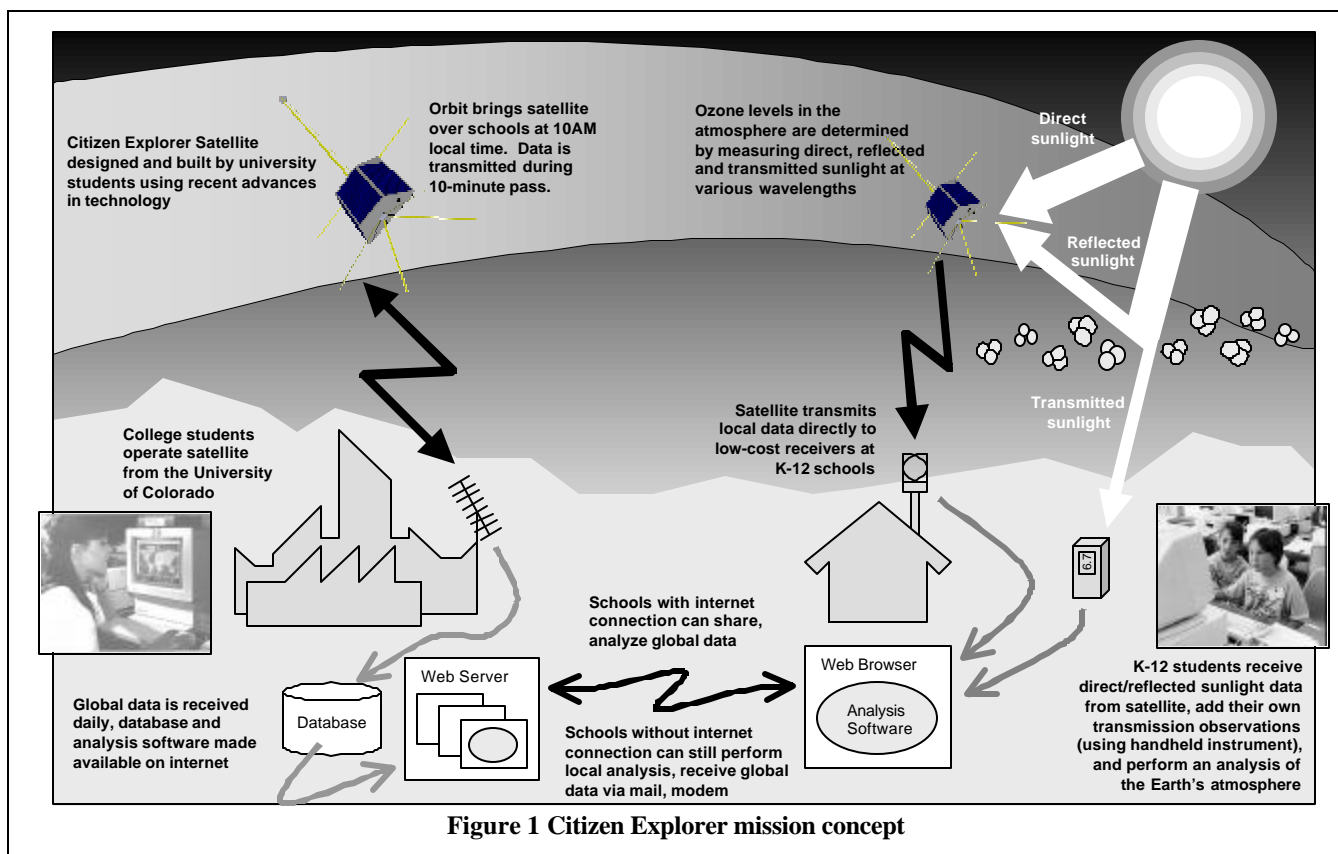
2. THE CITIZEN EXPLORER MISSION

The Colorado Space Grant Consortium (CSGC) is developing a series of Earth orbiting science satellites dedicated for use by K-12 students and teachers. This series of satellites will make up the Citizen Explorer Program, whose mission is to provide environmental and space education for K-12 students; significant experimentation for the scientific community; and real-world experience for undergraduate and graduate student engineers and scientists.

The Citizen Explorer - I (CX - I) satellite will be the first in this series of satellites. CX-I is designed for a sun - synchronous circular polar orbit with a 10:15AM/10:15PM equator crossing and an altitude of 705 km. The spacecraft has two science instruments including a spectrophotometer (Speck) which will measure UV-B and a photometer that measures visible reflectance. Additionally, there are two ground instruments including an UV-B detector and an aerosol meter. Data from these four instruments will complement each other to provide information about ozone levels in the stratosphere.

The focus of the CX-I project is education. Students (K-12) across the state of Colorado, the United States and eventually throughout the world will participate in this project. Participating schools will be equipped with a ground station (EduStation) which consists of an antenna, a personal computer and a receiver. Using the EduStation, each school will receive and process satellite data. This satellite data will be sent to the University of Colorado, Boulder via the Internet for further data processing. Using

¹ This paper is based on work done while the author was employed at the Colorado Space Grant College at the University of Colorado at Boulder.



this data, various data products will be made available to the schools. The schools will also make use of the ground instruments described above to make complementary measurements. In addition, schools will receive spacecraft health and status data, including beacon data, which will alert the schools to the state of the spacecraft as it is overhead. This allows the schools to serve as mini-mission control centers that can alert the CU Mission Operations team if the spacecraft is experiencing any problems.

The CX-I satellite and the Citizen Explorer Program is currently being designed and built by undergraduate and graduate students at the University of Colorado, Boulder with the help of other university students in the Colorado Space Grant Consortium and around the world. The CX team is composed of several subsystem teams responsible for all aspects of the program from flight and ground hardware and software, holding workshops for K-12 educators and actually operating the spacecraft during flight.

3. SYSTEM HISTORY

CXDOPS is a continuation of a highly successful program called the DATA-CHASER Automated Planning and Scheduling System (DCAPS). DCAPS was developed by JPL's Artificial Intelligence (AI) group to demonstrate the feasibility of automated planning and scheduling for space based payloads. This experiment was very successful in reducing operator time involved in producing schedules for

the DATA-CHASER Hitchhiker payload that was built by CSGC and flew in August 1997 on STS-85. During the flight DCAPS demonstrated the ability to reduce the time to produce a 12-hour schedule by a factor of ten and actually increased science data return from the mission by up 100% per viewing opportunity.

Given the payload model and an initial schedule for each operations cycle, DCAPS used AI algorithms to automatically complete and repair the schedule. The model was created in advance (pre-flight) and consisted of the inherent activity types, resources and constraints on the payload. The initial schedule originated from NASA attitude and event files specifying shuttle activities over the next 8-hour period. These files were parsed to extract those activities relevant to the payload, such as shuttle maneuvers and waste venting. The attitude determined what types of payload observations could be scheduled, while certain payload preparations were required during shuttle venting. Once the initial schedule was loaded, the DCAPS user generated a payload schedule using a set of predefined scheduling functions. For example, there was a function that scheduled payload power switching activities in appropriate places based on engineering parameters. Another function was used to schedule as many science observations as possible without violating any of the payload constraints. After generating the schedule, the user would manually validate the command sequence, making minor modifications as necessary. Finally, the validated sequence was

transmitted to the command and control system for execution during the next cycle.

Given DCAPS success it was decided that a follow-on system was warranted to look at further uses of emerging planning and scheduling technologies. This follow on system was to be useful in all phases of the mission not just the final operations phase. JPL's AI Group had demonstrated this concept with the Design for X (DXF) project.

The idea behind DFX arose from the observation that often it is difficult to determine how well a given spacecraft design will perform without fleshing out approximate operations sequences for critical phases of the mission (e.g., encounter). Automated planning and scheduling technology is used to evaluate candidate spacecraft designs from the standpoint of emergent design aspects such as science return and operability. Basically, DFX allows mission designers to quickly do many "what-if" scenarios while performing design trades. The different designs are encoded as different models used by the scheduler. By quickly generating a typical schedule for a given spacecraft model, designers can qualitatively measure the impact of their design on the science opportunities and resource margins. DFX helps ensure that science and mission operations have a more informed influence on spacecraft design.

4. CXDOPS IMPLEMENTATION

For CXDOPS to be successful in its goal to provide useful design analysis throughout all phases of the mission the required elements had to be identified. Using DCAPS and DFX as baselines these elements were identified as the following:

- Orbital dynamics modeling environment to provide orbit analysis and orbits events (Terminator crossings, ground station access times, etc.)
- A system modeling environment to provide system analysis and visualization.
- A mission-planning environment to support scenario development, and interface to advanced planning functions.
- A data analysis environment for detailed analysis.
- Simple interface between each of the elements and to the CX-I EEMOS.

Several requirements were placed on the CXDOPS architecture based on past experience with the DCAPS project. First, each of the elements had to be easy to interface to. Second user interfaces must be simple and easy to understand. Finally the system had to be able to perform all analysis required by the user upon receipt of a single command.

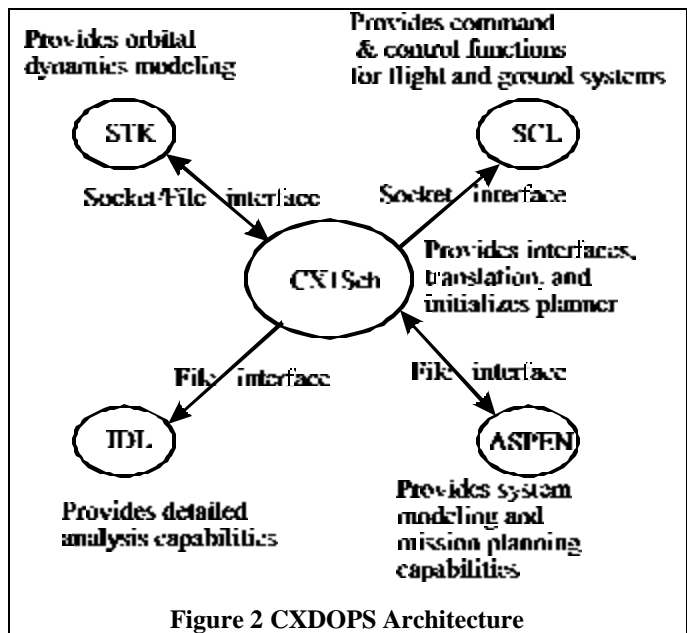


Figure 2 shows the architecture that has been implemented for CXDOPS. ASPEN (Automated Scheduling and Planning Environment) is the modeling and planning environment that was selected to provide system design and mission planning visualization. The Satellite Tool Kit (STK) provides the required orbital modeling and visualization for mission design. The Interactive Data Language (IDL) was chosen as the primary data analysis tool for CXDOPS. Finally the CX-I EEMOS team has selected the Spacecraft Command Language as the command and control system for both the satellite and ground systems. Each of these components is interfaced to the CX Scheduling (CXSch) program by either a file or socket interface. CXSch is the primary user interface for CXDOPS.

Mission Design/ Orbital Analysis

CXDOPS had to have an environment to input orbit data, and to reduce that data into products that the user and systems modeling and mission planning environments could interpret. In the case of DCAPS this was provided in the form of attitude files from NASA Shuttle operations. Since CX-I is a free flying satellite this would not be available.

The Satellite Tool Kit (STK) Commercial Off-The-Self (COTS) tool was developed and donated to CSGC by Analytical Graphics Incorporated (AGI). STK along with its analysis modules is a powerful mission design tool. STK has a GUI-based interface in which users can specify satellites and their orbits, planetary objects, and ground stations. The analysis package allows users to generate reports on everything from solar beta angle to ground station access times for a satellite. STK also features a socket interface, which can be used for another program to control STK's modeling and receive the analysis data.

In CXDOPS STK contains a model of the satellite, the CSGC ground station and all of the EduStations in use. During

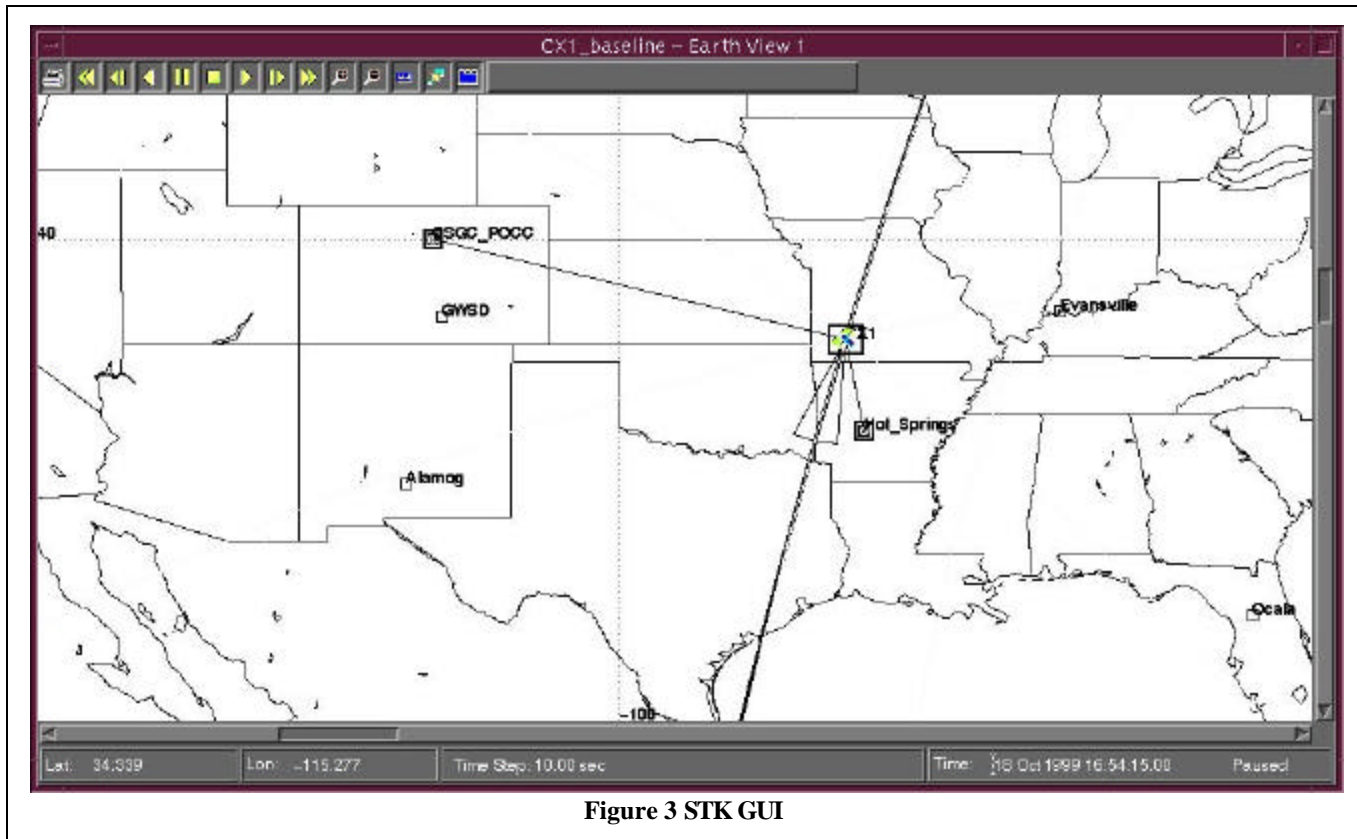


Figure 3 STK GUI

CXDOPS operations STK provides reduced orbit information such as ground station access times, terminator crossing times and solar beta angles to each of the 4 solar panels on CX-I. It also provides orbit visualization by animating the orbit for the selected period.

System Modeling

ASPEN (Automated Scheduling and Planning Environment) fulfills the system design visualization and mission planning requirements for the CXDOPS system. ASPEN is a reusable software framework for a wide variety of planning and scheduling applications. After an initial adaptation to a given application, ASPEN automatically generates command sequences from a set of high-level science and engineering goals. The initial adaptation includes developing a model of system activities, resources, state variables and constraints. Goals are given as incomplete activities with unresolved requirements. ASPEN includes a set of algorithms for developing a valid schedule of activities from the given goals.

ASPEN also provides a GUI for visualizing and manually editing the schedule. Conflicts (i.e. violated or unresolved constraints) are continually monitored throughout the schedule. An additional set of algorithms can be used for automatically repairing conflicts in a given schedule. These algorithms use a predefined set of generic repair methods that might be helpful in resolving various types of conflicts. Repair methods include moving, adding and deleting

activities. The repair algorithms search through the different ways of applying the methods in order to find a conflict-free schedule.

ASPEN's schedule visualization functions have been used by the systems designers as a way to visualize system interactions during the design processes. This has the added benefit of reducing the total modeling effort for the project as the initial model used in the design phase can be used by the mission operations teams as the basis for their model used for schedule generation and planning.

Data Analysis

Once we had started using the system for design visualization it was apparent that more detail was required to visualize some of the data. In particular, the change in solar array power over time needed to be displayed such that the effect of changing the orbit could be seen for each of the panels. We decided to use IDL (Interactive Data Language) to provide this capability. IDL is a language that has been tailored to meet the data analysis needs of the science community.

One of the plots generated by IDL is shown in figure 6. This particular graph shows the total power generated by each of the solar panels over the course of several orbits. Other capabilities available include graphing power generation over the course of a year, and a function that calculates the total Watt-hours produced in a given orbit.

| Azimuth(deg) | Elevation(deg) | Area(m ²) | Efficiency(%) | |
|--------------|----------------|-----------------------|---------------|--------|
| -30 | 0 | 0.0912 | 0.145 | Plusx |
| 210 | 0 | 0.0912 | 0.145 | Minusx |
| -90 | 0 | 0.0912 | 0.145 | Minusy |
| 270 | 30 | 0.0608 | 0.145 | Minusz |

☐ Run Power Analysis
 Initial Battery State (mW-sec): 110000000
 Power Interval(sec): 60

Execute Scheduler

Figure 4 CXSch Power System Interface

User Control

Once the tools that were needed were defined, a user-friendly interface had to be developed. These interfaces had to facilitate communication between each of the CXDOPS elements transparent to the user. These requirements evolved into the CX Scheduling (CXSch) program developed by CSGC.

At the core of CXSch are several Java classes that are responsible for the interfaces between each of the elements of the system. Java was chosen as the primary language because it lends itself well to distributed computing. In addition, being object oriented will make it easier for many of the routines written for CXSch to be used for similar systems for other satellites and spacecraft.

CXSch provides the GUI through which the user controls the system by input parameters that determine what analyses that the CXDOPS will perform. This GUI allows the user to change over 20 design parameters and select which of the 6 different analyses to perform. An example of one of these interface panels can be seen in Figure 4.

This power interface panel allows the user to change the angles that the solar panels are mounted to the satellite as the structure is modified to optimize the power generated by the panels over an orbit day. In addition the user can change the efficiency, and area of each of the solar panels individually. The "Run Power Analysis" checkbox allows the user to select whether or not to run the IDL power analysis program. The "power interval" variable allows the user to select the time between samplings of the power generated by the arrays. The "Initial Battery State" variable is used by ASPEN to set the state of the battery at the beginning of the modeling window.

To run the CXDOPS system the user runs the CXSch program and starts STK. Once the CXSch GUI comes up the user sets the scheduling window (period of time) that they want to look at, change the necessary design parameters, and selects what analysis they want run and the files the data should be written to. With this data CXSch starts the process of performing the required analysis.

The first step is to load the STK model and propagate the orbit for the CX-1 satellite and the AM-Sat satellites (if requested) for the time window specified. Once completed CXSch asks STK to perform the orbit-related analysis asked for by the user, such as ground station contact windows, link budgets, etc. The results for this analysis is written to files specified by the user. Once this is complete CXSch will perform the necessary translations so that the STK data can be used by the other components of CXDOPS.

Once the translations are completed CXSch starts the power analysis visualization in IDL if the user has requested that this be done. If the user asks that ASPEN be run CXSch will start ASPEN automatically with the data from STK and an initial schedule generated by CXDOPS for ASPEN to repair and optimize.

During mission operations users will have the option of sending the final schedule generated by ASPEN directly to the satellite command and control system SCL. This is accomplished by CX1Sch reading in the ASPEN generated command file and translating it to a SCL command format and sending those commands to SCL via a socket interface.

5. DESIGN VISUALIZATION

CXDOPS has been used throughout the design process to analyze various aspects of the CX-I design. CX-I is a highly

constrained satellite. First it is being designed and built by students who have limited resources both monetarily and experience. Secondly being a secondary payload the design is very tightly constrained in volume and mass. Add to that the program requirements of downlinking to a large number of very small ground stations and testing advanced mission operations technologies and this design has become fairly complex.

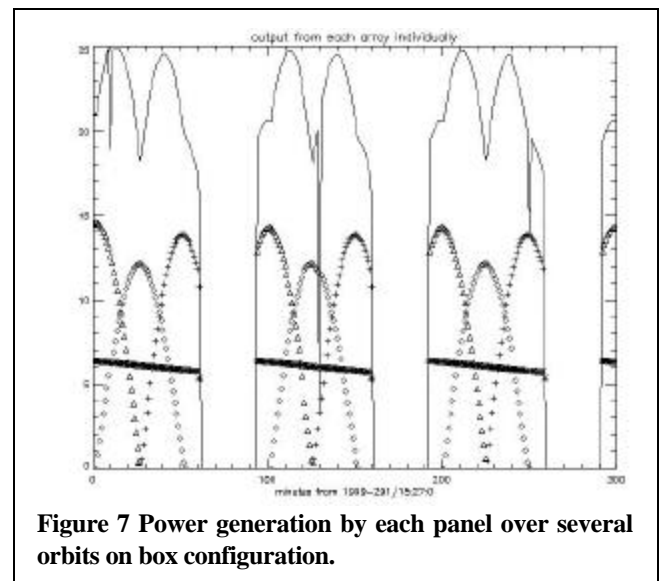
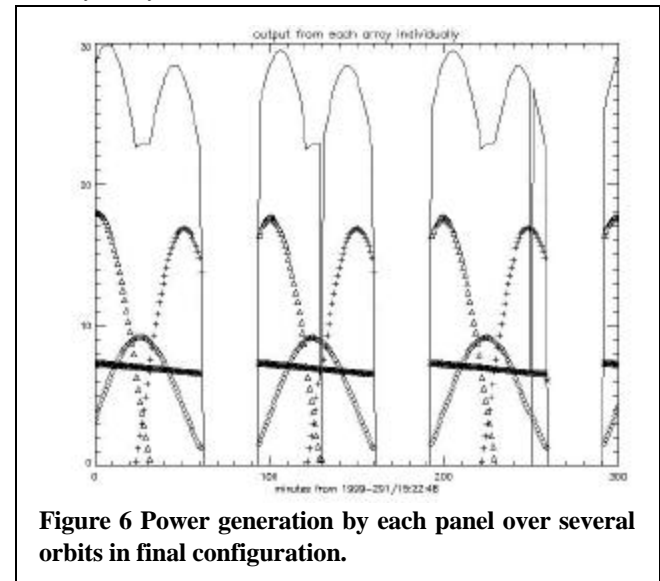
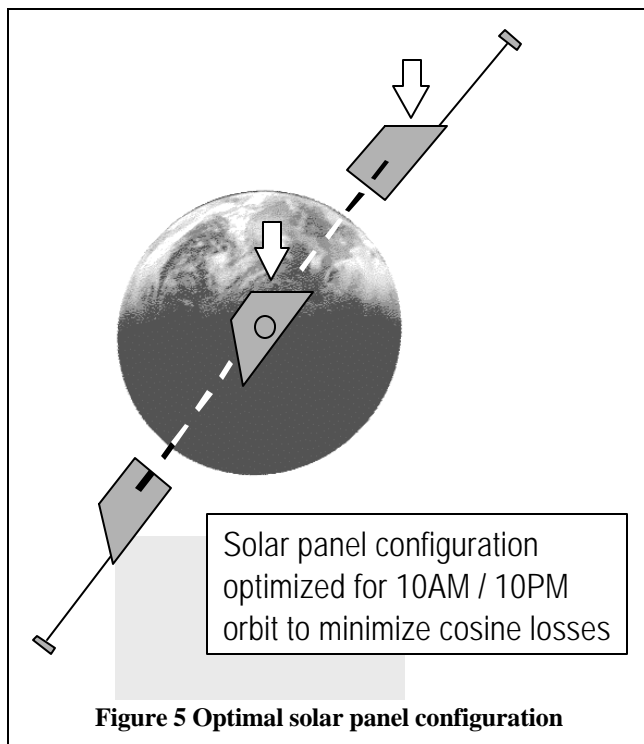
As the requirements listed above have matured and have become better understood by the design team the CX-1 design has been modified to meet these requirements. These design changes had to be modeled in order to visualize how they would effect the satellites performance. CXDOPS has greatly reduced the time that it takes to perform these analyses. This capability has allowed designers to use a “guess and check” approach at times to build a more intuitive knowledge of how their subsystem performs and what parameters of their design are the most sensitive to changes in system design as well as their own.

The power system of CX-1 was one of the major users of this system. This was due to the program and system requirements placed on its design. The power system was tasked with providing 24-26 W-hrs per orbit. This requirement was driven by the C&DH system (high power computer to run high power software), and the communications system (driven by link budget to EduStations and high duty cycle (>20%)). A further driving requirement limited the power design team to only consider body mounted solar arrays. This was done due to the need to reduce the number of mechanisms, and hence the system complexity. The design was further complicated due to the

limited total volume constraint placed on the design by the launch vehicle.

The design of the power system was where CXDOPS really proved its value to the design team. By working with the CXDOPS several structural configurations were analyzed quickly (each under 10 min.). Through this analysis the configuration shown in Figure 5 was able to produce the maximum power for the design orbit. The top and side panels were angled so that over the course of an orbit the power generated by the panels remains fairly consistent.

This configuration using Gallium Arsenide cells produces a minimum of 26 W-hrs per orbit during the first year of operations. In figure 6 the power generated by each of the panels over the course of a couple of orbits can be seen. For the current configuration the energy margin is 7% during the lowest power generation period of the year. In Figure 7 the power profile generated by a “box-like” design which was initially analyzed can be seen.



While the solar array design has been optimized as much as possible there are still scenarios in which the satellite has a negative energy margin on an orbit to orbit basis. The systems model in ASPEN has been very helpful in visualizing this situation and helping the systems and mission operations teams find solutions that meet requirements.

One of these scenarios includes an orbit with a long pass over CSGC followed by an orbit with several EduStation passes along the Pacific Coast. These two orbits both have negative energy margins and the batteries are used to make up to deficit. Using ASPEN it was seen that this deficit is made up on the following orbits while the satellite is over the Pacific Ocean. Other scenarios that have been analyzed include night CSGC passes, a missed pass and it's effect on data storage, and communications conflicts with other satellites with similar communications frequencies (AM-SAT).

Several capabilities of CXDOPS were developed late in the design process and were not utilized by the CX-I design team. CXDOPS has the ability to generate link budget reports for the communications team. Interfaces for use by the ADCS team, including the ability to load an external attitude file into STK, and the ability to set a constant offset from the default attitude.

6. MISSION OPERATIONS

One of primary objectives of the CX program is to demonstrate advanced mission operations technologies. For the CX-I mission one of these is to demonstrate advance mission planning technologies, including automated plan generation and schedule conflict resolution. CXDOPS provides the test bed in which these technologies can be demonstrated.

The ultimate mission operations goal of CXDOPS is to build upon the success of the DCAPS program, by further demonstrating the use of autonomy to minimize operator involvement in the day-to-day planning operations of the satellite. This will reduce the amount of personnel required to operate the satellite and hence lower the operations cost over the course of the mission.

CXDOPS will also take advantage of the conflict resolution and plan optimization capabilities of the selected mission planning tool ASPEN. The conflict resolution capabilities will try to resolve the conflicts that will arise due to the fact that CX-I is extremely power constrained. Another potentially serious set of conflicts will be between some of AM-SAT satellites that share our communications frequencies. At the same time CXDOPS will strive to maximize science return and the number of EduStations to which data is sent.

During mission operations once the user has adjusted the input parameters for the scheduling window they are interested in CXDOPS will perform the following functions:

- Perform orbital prediction and analysis for CX-I orbit in the scheduling window specified
- Insert and report access times to all requested schools
- Perform power analysis.
- Create initial goals and activities for the planning system.
- Fix and optimize initial plan.
- Ask user for permission to send optimized plan.
- Translate planner activities to SCL commands
- Send commands to ground system run-time engine (RTE) for uplink to spacecraft.

At this time CXDOPS has the ability to generate the pointing control file for the ground station. Use of this capability during operations is currently under review.

A future capability currently under study is automated re-planning. This would be accomplished by further integration between ASPEN and SCL. Re-planning would occur at the beginning of a given CSGC communications pass. The current state of CX-I would be relayed to ASPEN by SCL and the schedule generated prior to the pass would be checked for conflicts, any which show up would be resolved. After all conflicts are resolved the user is asked permission to send the new schedule to SCL for uplink to CX-I.

7. CONCLUSION

CXDOPS has proven itself to be useful throughout all phases of the design process. It has also shown that it is possible to use the same spacecraft model for design verification and mission planning saving both time and resources. During mission operations CXDOPS should show that integrating an automated planning and scheduling system into the end to end mission operations system will reduce operator involvement in the planning operations of the satellite and hence reduce operations cost.

REFERENCES

- [1] G. Rabideau, S. Chien, C. Eggemeyer, T. Mann, J. Willis, S. Siewerts, P. Stone, "Automating Schedule Development for Shuttle Payload Operations," *International Workshop on Planning and Scheduling for Space Exploration and Science*, October 28-30, 1997
- [2] R. Shepperd, J. Willis, E. Hansen, J. Faber, S. Siewert, G. Rabideau, "DATA-CHASER A Demonstration of Advanced Mission Operations Technologies," *IEEE Aerospace Conference Proceedings*, March, 1998
- [3] J. Owens, "Designing for Mission Success: The System Architecture of Citizen Explorer I," *AIAA Region V Student Paper Conference*, March, 1998

[4] R. Sherwood, S. Chien, G. Rabideau, T. Mann, "Design for X (DFX): Operations Characteristics Spacecraft Design Analysis Tool," *International Workshop on Planning and Scheduling for Space Exploration and Science*, October 28-30, 1997

Jason Willis is a Member of the Technical Staff in the Spacecraft Systems Engineering Group at the Jet Propulsion Laboratory, California Institute of Technology. Prior to JPL Jason worked at the Colorado Space Grant College for 6 years. First as electrical integration team lead on the ESCAPE II shuttle payload that flew on STS-66. Following that flight he spent the following 3 years as the lead systems engineer for the DATA-CHASER Hitchhiker payload which flew on STS-85. Since 1997 he has worked on the Citizen Explorer project as power system lead, member of the systems engineering team and is currently an advisor. Jason holds both a B.S. and M.S. degree in Aerospace Engineering Science from the University of Colorado at Boulder where he specialized in spacecraft systems.

Gregg Rabideau is a member of the Artificial Intelligence Group at the Jet Propulsion Laboratory in Pasadena, California. Gregg earned his B.S. and M.S. degrees in Computer Science at the University of Illinois where he specialized in Artificial Intelligence. His main focus is in research and development of planning and scheduling systems for automated spacecraft and rover commanding. Gregg is currently working on planning and scheduling for future Mars rover missions. Past projects include the New Millennium Deep Space One mission and the DATA-CHASER shuttle payload.



Colette Wilklow is currently pursuing a Bachelors Degree in Computer Science from the University of Colorado Boulder. She has worked at the Colorado Space Grant College for the past 3 years. She worked on the power and mission operations teams for the DATA-CHASER payload that flew on STS-85 in August of 1997. She is currently working on the Citizen Explorer small satellite as the leader of the mission operations team.